Precision Autonomous Landing Adaptive Control Experiment (PALACE)

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ABSTRACT

This paper describes the development, flight-testing and demonstration of technologies for the autonomous landing of a Yamaha RMAX helicopter at non-cooperative sites without the aid of GPS. The Yamaha RMAX used for these flight trials has been modified to include stereo cameras, a laser range finder, and an avionics payload. Machine vision stereo range mapping is used to generate an accurate terrain representation, and a safe landing area determination algorithm is used to select the safest landing point within the terrain. A machine vision self-localization system is used to measure the helicopter position during the descent and landing when GPS is unavailable. The software and hardware architecture of the flight system is presented and each system component is described. Results and lessons learned from the flight evaluation and optimization of the individual components are reported as well as the overall system performance with respect to a set of objective metrics for the autonomous landing flight trails.

1. INTRODUCTION

With the intent of the US armed forces to field an increasing number of Unmanned Aerial Vehicles (UAVs) as part of the Future Combat System (FCS), particularly Rotorcraft UAVs (RUAVs) and other Vertical Take-Off and Landing (VTOL) UAVs, there is a clear need for an autonomous landing capability to remote, unprepared (and possibly cluttered) sites. Such a capability would also need to include a self-localization component since GPS signals may be intermittent or unavailable during the landing task due to electronic jamming or occlusion of GPS satellites. In addition to the difficulty of finding a suitable landing point and navigating to this landing point without GPS, all terrain sensing, information processing and decision-making functions must be performed on-board without the need for operator interaction. Typical operational scenarios that would benefit from such a capability include: perch-and-stare surveillance operations; ground loiter to conserve fuel and other system resources; precision supply delivery and Forward Arming and Refueling Point (FARP) operations; remote recovery of the RUAV; and forced landing contingencies resulting from on-board failures or loss of communication.

Current technologies for the landing of UAVs are mostly limited to using an external pilot, recovery net, or auto-land system requiring specially prepared and instrumented landing sites. These technologies often preclude UAVs from landing autonomously or from landing in un-prepared environments where the terrain profile is uncertain and possibly cluttered.

The Precision Autonomous Landing Adaptive Control Experiment (PALACE) Army Technology Objective (ATO) was formulated to address some of these current limitations by developing, integrating and demonstrating technologies for reliable, autonomous landings of RUAVs. The PALACE program was a three-year activity (completed in FY06) performed by the US Army Aeroflightdynamics Directorate (AFDD) at Moffett Field in California and concluded with a public demonstration of a Yamaha RMAX helicopter making a number of successful landings to cluttered landing sites without the aid of GPS for navigation. Supporting efforts were provided by the Army/NASA Autonomous Rotorcraft Program (ARP), Brigham Young University (BYU), and the Mobility and Robotics Group at JPL.

The technical approach developed to achieve autonomous landing capabilities first uses passive stereo ranging to build a 3D terrain profile of the potential landing site. The stereo ranging algorithm uses a pair of images from digital cameras mounted on the helicopter to build the 3D profile of the terrain visible in both cameras.

A landing site selection algorithm then inspects the terrain map to determine if the site is suitable for landing and to select the point that best meets a set of vehicle and mission landing site requirements. The requirements ensure that the chosen landing point has a surface slope within the physical capabilities of the helicopter, is a minimum distance from obstructions, and has a surface roughness below a given threshold.

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 NOV 2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Precision Autonomous Landing Adaptive Control Experiment (PALACE)**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army Aeroflightdynamics Directorate (AMRDEC) Ames Research Center, CA**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM002075., The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**27**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Navigation to the selected landing point without GPS is achieved using machine-vision self-localization algorithms that provide the helicopter position relative to the ground terrain as the helicopter descends to the chosen landing point. Stable hover and descent is achieved using this system over various surface textures without ground based markings or instrumentation.

Initial work on the PALACE program independently demonstrated each of the core machine vision technologies (Hintze et al., 2004), and validated their utility in both simulation and flight. This was followed by the construction of an integrated simulation environment (Theodore et al., 2005) for the development of the landing procedures and integration of the machine vision algorithms, vehicle dynamics, and control laws. The performance of the individual machine vision algorithms was evaluated using the simulation. The simulation also provided a level of risk reduction when transitioning the PALACE landing technologies to flight trials. Finally, flight development, testing and validation of the autonomous landing technologies were performed on a Yamaha RMAX RUAV (Theodore et al., 2006). The in-flight performance of the individual technologies was evaluated, as well as the overall performance of the landing system. Repeat successful landings were performed to a number of different surfaces, with different obstacle fields, and with variable wind conditions.

Table 1 lists the quantitative metrics and target performance objectives for the PALACE program. The first three metrics are constraint values for the landing site selection algorithm and, for this case, are a function of the geometry of the Yamaha RMAX helicopter. The following metric specifies the landing accuracy and accounts for drift in vehicle position during the vision-based descent. The next requirement specifies that the self-localization must run with a processing time of less than 100 msec in order produce a position estimate at 10Hz. The final two objectives specify that the landing site selection algorithm should choose a safe landing site in under 5 seconds with a greater than 98% success rate.

This paper first gives an overview of the fight software and hardware architecture and describes each of the individual components. This includes the on-board mission manager element that coordinates each component of the system and provides all of the intelligence and decision-making capabilities to enable autonomous landings. The next section presents results from the flight trials on the Yamaha RMAX, including stereo range mapping, landing site selection, and self-localization without GPS. The final section presents concluding remarks and discusses the ability of the PALACE system to meet the set of objectives listed in Table 1.

Table 1. PALACE program performance metrics and objective values for the Yamaha RMAX vehicle.

Quantitative Metric	Project Objective
Landing Site Size	< 7.0 m
Landing Surface Slope	< 15 deg
Landing Surface Roughness	< 10 cm
Landing Accuracy	< 1.25 m
Feature-Tracking Cycle Time	< 100 msec
SLAD Calculation Time	< 5 sec
SLAD Success Rate	> 98%

2. PALACE SYSTEM ARCHITECTURE

Figure 1 shows a schematic of the hardware and software architecture used for the PALACE flight trials. Each element of this architecture is described in the following sections.

2.1 ARP RMAX hardware and sensors

The flight trials and demonstrations for the PALACE program were performed using a modified Yamaha RMAX that is part of the Army/NASA Autonomous Rotorcraft Project (ARP) (Whalley et al., 2003). The Yamaha RMAX is a small-scale helicopter with a rotor diameter of 3.12 m and an empty mass of 66 kg. The maximum payload is 28 kg.

The RMAX operated by ARP (Figure 2) has been modified to include an avionics payload and various sensors. The avionics payload includes: a navigation and flight control computer, an experimentation computer, an IMU, a GPS receiver, and communications equipment. The experimentation computer is a compact-PCI with a Pentium III running at 700Mhz and hosts the PALACE software and machine-vision algorithms. A pair of monochrome 640x480 resolution stereo cameras are mounted on either end of a vibration-isolated articulated stub wing with a stereo baseline of 1.1 m. Figure 3 shows the camera arrangement on the left end of the stub wing with monochrome and color cameras (the PALACE system uses only the monochrome camera for stereo ranging). Finally a SICK scanning laser is mounted under the nose. For the PALACE flight tests, only the laser return to the ground at the center of the camera image is used to simulate a simple laser range finder.

2.2 ARP flight control laws (CLAW)

The CLAW block of the flight architecture (see Figure 1) contains the inner-loop and outer-loop control

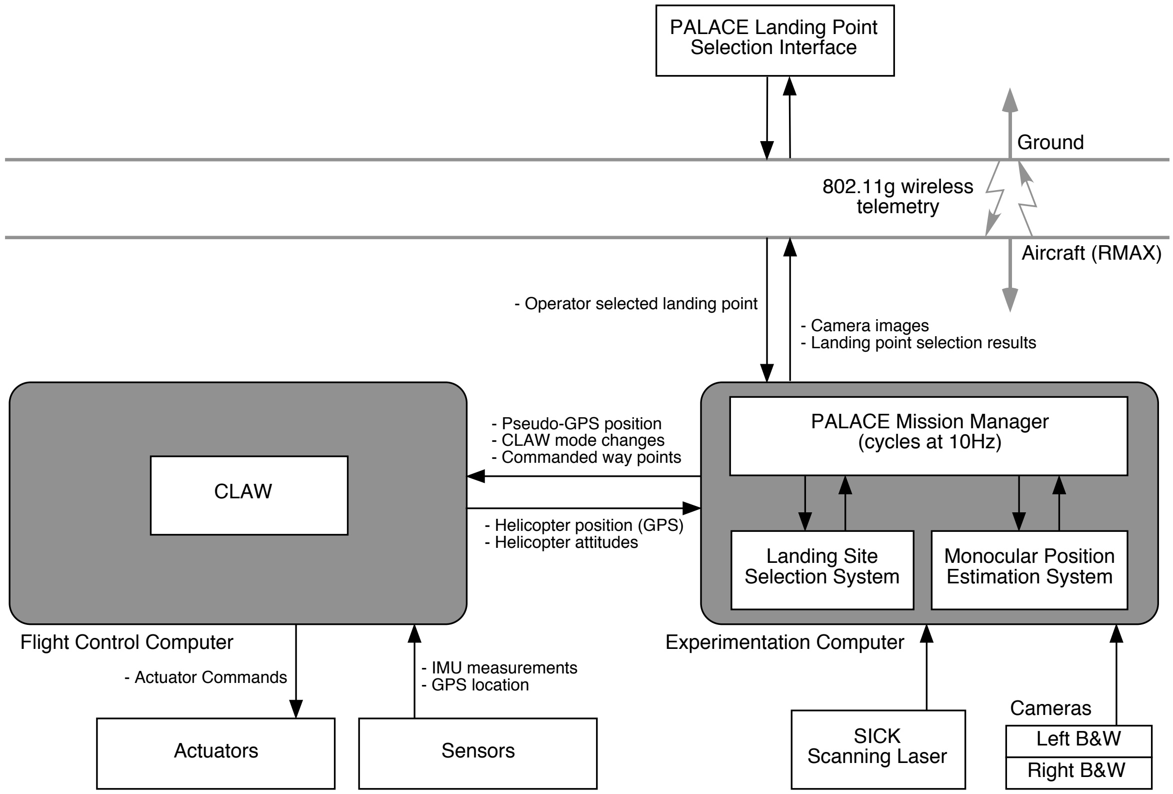

Figure 1. PALACE flight hardware and software architecture.

Figure 2. ARP RMAX research aircraft.

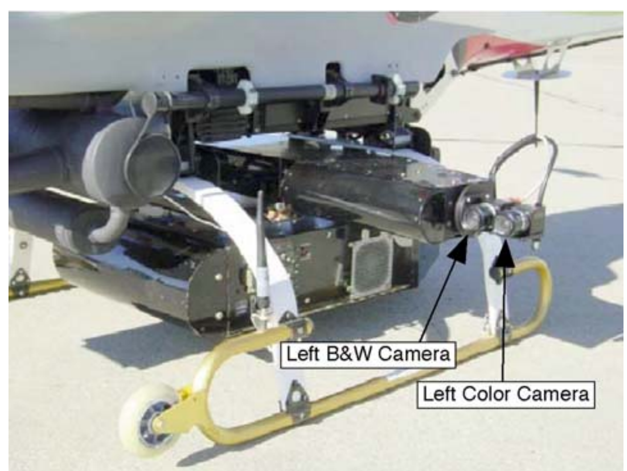

Figure 3. ARP RMAX avionics payload and stub wing with left cameras.

laws, as well as the mode switching elements. The inner-loop provides the primary attitude stabilization and attitude control of the helicopter. The outer-loop includes a waypoint navigation controller, which is made up of a path smoother and a path follower. When a list of waypoints are received into the CLAW block (from the operator or from the PALACE mission manager) they are first passed to the path smoother, which produces a larger list of waypoints that describes a smooth path between the original waypoints. The path follower then takes the desired smooth path and provides a steady stream of commands to the inner-loop to guide the helicopter along the path.

The CLAW block provides a number of different modes for localization during waypoint navigation. The default is to use the signal returned by the on-board GPS receiver for navigation. A second mode allows an external position to be input into the CLAW block, which is then used for navigation. In the PALACE

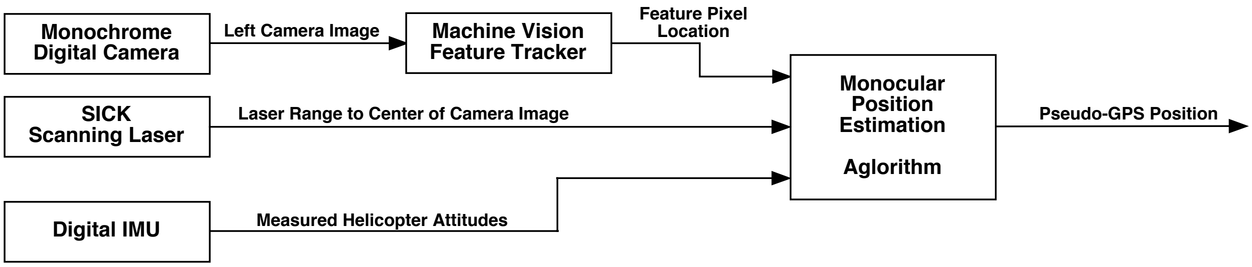

Figure 4. Flowchart of MPE processing.

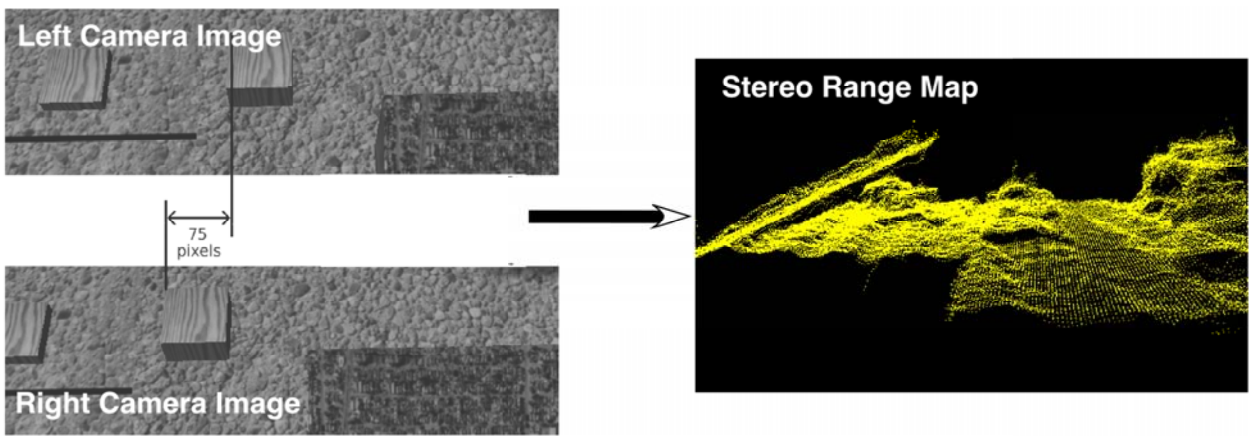

Figure 5. Stereo images and resulting range map.

architecture, this external position is the 'pseudo-GPS' signal from the machine-vision position-estimation system. A third mode uses inertial navigation to provide a position estimate based on the attitude and acceleration measurements. Each of these navigation modes is selectable by sending a request to the CLAW block, which produces a smooth, transient-free transition to the selected mode.

2.3 Monocular position estimation (MPE) system

The MPE system provides a helicopter position that is independent of GPS and is used for navigation during the landing when GPS is assumed to be unavailable. The MPE system takes the left camera images, the laser range to the center of the camera image, and information about the pose of the camera to measure the position of the helicopter relative to a fixed point on the ground that is being tracked over time.

Figure 4 shows a schematic of sensor data processing to produce the position estimate. The machine-vision feature-tracking algorithm was developed by JPL (Johnson et al., 2001) and is able to lock onto surface features and accurately track them from frame to frame. The MPE system runs in real-time at 10 Hz and produces a pseudo-GPS position estimate. The rate and format of the pseudo-GPS signal is the same as the signal from the GPS receiver, which required no changes to the control system to integrate the machine-vision position estimate. Additional details of the MPE system can be found in Ref. (Theodore et al., 2006).

2.4 Landing site selection system

The landing site selection system used for the PALACE program consists of two steps. The first step involves creating a stereo range map to represent the surface terrain profile. The stereo ranging algorithm utilizes images from a pair of stereo cameras along with pose information for the cameras. The stereo range map is created by determining pixel disparities between features in the left and right camera images (Figure 5).

The second step in the landing site selection process utilizes a Safe Landing Area Determination (SLAD) algorithm. This algorithm applies a set of landing point constraints to the range map to find all safe landing regions, and then to choose the optimum landing point. Three constraints on the landing point are applied to ensure the surface slope is below a given tolerance, any surface obstructions or roughness are below a given size, and the range to the nearest obstacle is greater than a given distance. For the ARP RMAX the slope limit is

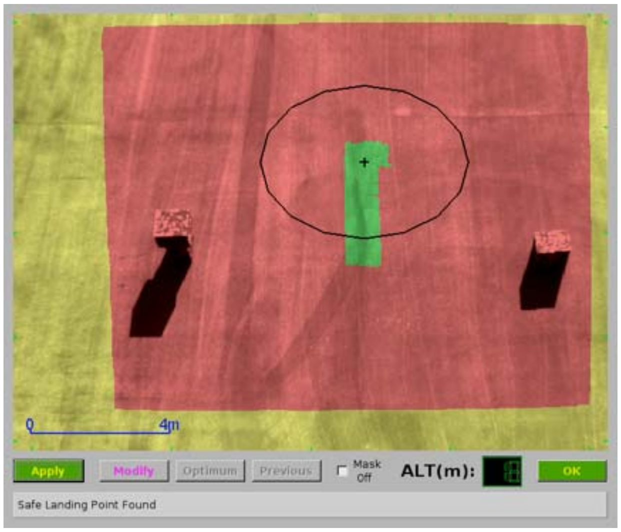

Figure 6. SLAD operator interface showing results of landing point selection.

set to a maximum of 15 degrees, and the safe distance constraint (open-area diameter) is a minimum of 7.0 m.

The roughness constraint defines the maximum allowable size of ground features or obstructions for landing. Any terrain roughness or surface objects physically larger than the roughness constraint value will be recognized as obstacles by the SLAD algorithm and the surrounding terrain will be rejected as a safe landing area. Since the resolution of stereo ranging varies with the physical distance above the ground, the value of the roughness constraint must be set dynamically based on the height above ground level (AGL). For example, from 6 m AGL, the system is capable of rejecting landing sites with obstacles as small as 10 cm, while from 30 m AGL it can reject sites with obstacles only as small as 1.2 m. Therefore, the landing point selection system has to be run at different altitudes during the descent with successively tighter roughness constraint values.

Figure 6 shows an example of the SLAD operator interface. The display shows results from the safe landing site selection system, in this case with two obstacles in the camera field of view. The yellow region shows the portion of the camera image where no range data are available due to non-overlapping left-right image features or the close proximity of the edge of the image. The points in red violate one or more of the landing point selection constraints and are determined to be unsafe for landing. For this particular case, the points in the red region are either too close to the obstacles, or too close to the inner edge of the yellow region, which is treated as an obstacle since no terrain range information is available beyond this border. The green region indicates the points that meet all of the constraints and are considered safe to land. Finally, the black '+' indicates the point that best meets the constraints, and the circle shows the diameter of the safe-distance constraint.

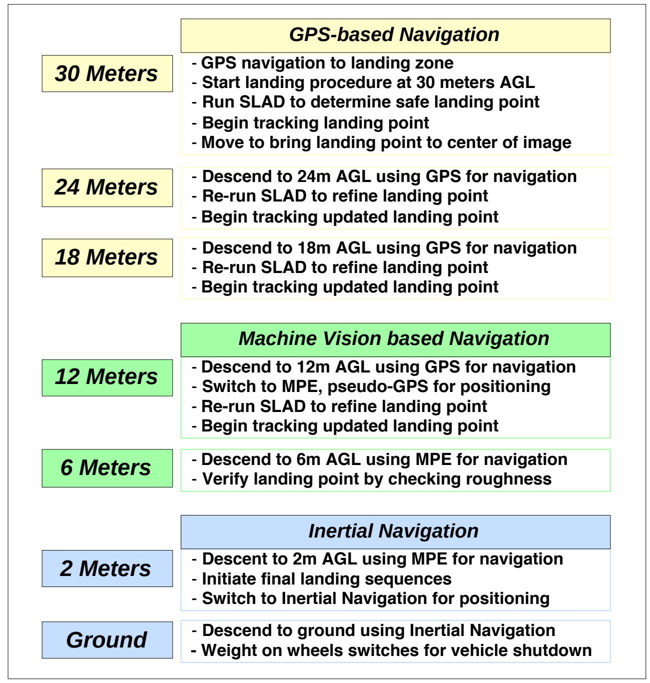

Figure 7. PALACE landing sequence during the descent from 30m to the ground.

The information in Figure 6 is presented to the operator each time a new landing point is selected and allows the operator to verify the landing point. The operator also has the option of selecting an alternate landing point if necessary.

2.5 PALACE mission manager

The PALACE mission manager software is the heart of the system and unifies the various elements. It also provides the decision-making and coordination capabilities required to fly complete PALACE landings. Figure 7 shows the steps in the PALACE landing procedure as the helicopter descends from 30 m AGL to the ground.

The landing procedure starts with the helicopter arrival at the landing zone, which has been specified by the operator as a general location rather than a specific landing point. The cameras on the RMAX are set to a pitch angle of -60 degrees so that the helicopter will descend and land at this angle. The descent angle, or glideslope, is set the same as the camera angle so that the landing point remains nominally in the center of the camera image as the helicopter descends.

The helicopter moves under GPS waypoint navigation to view the nominal landing point location specified by the operator from an altitude of 30 m AGL.

At this point, the stereo ranging and SLAD algorithms are run to select an initial landing point that best meets the set of slope, roughness and safe distance constraints. The machine vision feature-tracker estimates the location of the landing point and starts tracking this point. The PALACE mission manager then calculates and sends a waypoint to move the helicopter laterally and vertically so that the selected landing point will be in the center of the camera image from 24m AGL.

At 24 m, the stereo ranging and SLAD algorithms are run again to refine the landing point location with a tighter roughness constraint to reject regions with smaller obstacles that could not be detected from the higher altitude. The feature-tracker is then re-initialized with the updated landing point and a waypoint is set to bring this point to the center of the camera image. Another waypoint is set at an altitude of 18 m along the glideslope and the vehicle descends further. The same procedure happens at 18m AGL to bring the helicopter down to 12m AGL.

At 12 m, the CLAW block is instructed to switch from GPS to the pseudo-GPS position estimate returned by the MPE system for navigation. The descent and landing from this point is flown entirely without using GPS. The SLAD algorithm is run again to refine the landing point and the helicopter descends to 6 m AGL.

At 6 m AGL, the stereo ranging and SLAD algorithms are run for the final time to verify that the final landing zone is obstacle-free (within the final roughness constraint value) and safe for landing. Once the final landing point has been verified, the helicopter descends to 2 m AGL where the command to initiate the final landing script is given. The helicopter begins the final descent using MPE for navigation. When MPE goes out of range (too low for reliable tracking), CLAW switches to inertial navigation for the final portion of the landing. The total time while in inertial navigation is generally less than about 10 seconds so that there is little drift in the absolute position during this period. Weight-on-wheels switches are triggered when the vehicle touches the ground to complete the landing.

3. FLIGHT TEST RESULTS

Among the most critical technologies for the automated landing task are the machine vision algorithms and the integration of these algorithms with the RMAX hardware and control laws. Component flight tests were first performed to validate and optimize the in-flight performance of the various machine vision elements. Following this, flight trials of the complete system were performed to validate the mission manager functionality and decision-making capabilities, the integration of the machine vision elements into the complete landing procedure, and the smooth transition between different control modes. This ultimately led to complete landings on various surfaces and obstacle fields. Upwards of 30 flights to-date have included test points for the development and evaluation of the PALACE components and system (Theodore et al., 2006). Upwards of 40 successful landings using the complete system have been performed to date on various surfaces and obstacle fields.

3.1 Monocular position estimation (MPE) evaluations

The monocular feature-tracker and MPE algorithms take left camera images, the laser range to the center of the camera images, and information about the pose of the camera to estimate the position of the helicopter position relative to a fixed point on the ground. This allows the MPE system to provide a self-localization capability that is used for navigation during the final portion of the descent from 12 m AGL to the ground without GPS.

The performance of the MPE system was evaluated in-flight for a number of different conditions, including variations in atmospheric conditions (wind speed, wind direction and level of turbulence), lightning conditions (overcast and full sun), surface textures (grass, concrete, asphalt and gravel), and height above the ground. The performance metrics that were evaluated during flight were the amount of tracking drift, the processing time required for each cycle of tracking and position estimation, and the ability of the helicopter to hold position and maintain the correct descent path while navigating to the ground.

Flight tests of the MPE system in separate hover, climb and descent tests revealed that MPE is robust for different surfaces, with similar performance seen over grass, concrete, asphalt and gravel. MPE is also robust to lighting conditions (overcast and full sun) and atmospheric conditions (wind speed, wind direction and level of turbulence) with similar amounts of tracking drift seen in each case. The total amount of tracking drift observed in each case was small and limited to about 15-20 cm per minute.

Figure 8 shows the Easting, Northing and height time histories during a climb from 12 m AGL to 30 m AGL using the vision-based self-localization system. The total amount of drift for this case after about 5 minutes without GPS was less than 1 m. This amount of drift is well within the 2 m margin included in the SLAD safe distance constraint to account for tracking drift, particularly since the amount of time to navigate from 12 m AGL to the ground is only on the order of one to two minutes.

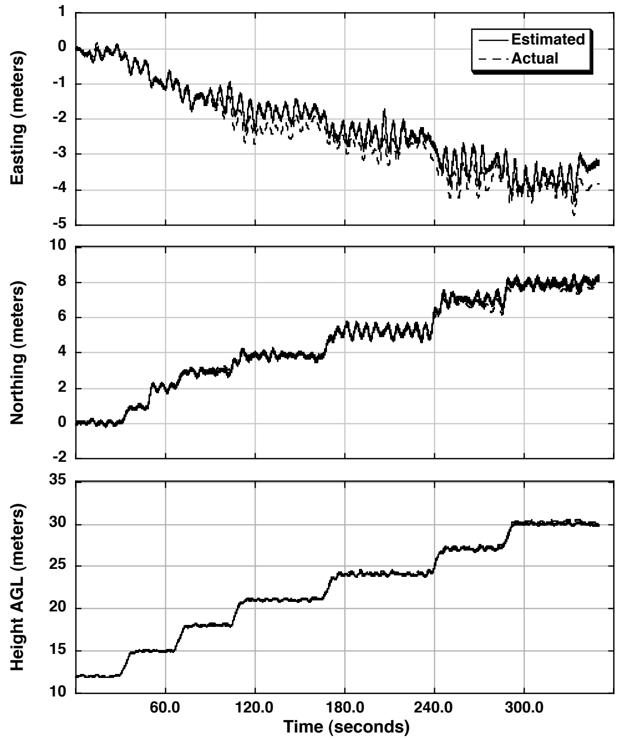

Figure 8. Time histories comparing actual position (GPS) and estimated position (MPE) for a climb from 12m AGL to 30m AGL.

3.2 Stereo ranging evaluations

The generation of an accurate range map from a pair of stereo camera images is the key element in the selection of a safe landing point. If the range map does not represent the ground terrain and obstacles with sufficient accuracy, then the SLAD algorithm may not select the best, or even a safe landing point, and may also reject a potentially safe landing point.

The key performance measure associated with stereo ranging is the amount of uncertainty (or noise) in ranging flat ground, which gives an indication of stereo ranging resolution. The resolution places a lower limit on the size of obstacles that can be resolved from the ranging noise and is used as the basis for setting the roughness constraint values for the SLAD algorithm.

Table 2 lists the roughness constraint values versus height for asphalt and grass surfaces. These values are derived from the amount of noise in the stereo range maps observed when ranging flat surfaces, and represent the size of obstacles that are clearly distinguishable from the noise in the range maps. These roughness constraint values therefore place an lower limit on the size of

Table 2. Roughness constraint values as a function of altitude for asphalt and grass.

	Roughness Constraint (m)	
Height AGL (m)	Asphalt	Grass
30	1.20	1.50
24	0.80	1.00
18	0.40	0.55
12	0.25	0.30
6	0.10	0.10

obstacles that will cause a surface to be rejected by the SLAD algorithm. Obstacle sizes less than these values may or may not be rejected. The values indicate that from 6 m AGL over asphalt, the system will reliably reject landing surfaces with obstacles of height 10 cm and taller.

3.3 SLAD flight evaluations

The SLAD algorithm takes a range map and combines it with a set of landing point constraints to first calculate a safe landing map, and second, choose the optimum landing point. For the PALACE program, the range maps were generated using stereo ranging, but the SLAD algorithm can be used with range maps from any sensor, including active as well as passive sensors.

The constraint values used for the PALACE flight trials are based on the geometry and performance limits of the Yamaha RMAX. The landing site slope constraint value was set to 15 degrees, although all landings performed with the RMAX were on slopes below 5 degrees. The safe distance constraint is set to 7 m to ensure the algorithm selects a landing point with an open-area diameter of at least 7 m. This leaves a margin of 2 m from the rotor tip to the nearest obstacle.

The success or failure of the SLAD algorithm is based its performance in choosing a valid landing site. A success occurs when the algorithm correctly identifies a safe landing point when one exists, or when it correctly identifies no safe landing sites when none exist.

The performance of the SLAD algorithm was evaluated in-flight for a number of different landing scenarios, with variations in surface texture (asphalt, grass, concrete and gravel), obstacle field (size, density and spacing), height above the terrain, and SLAD constraint values. With an accurate representation of the surface terrain in the form of a 3D range map, the SLAD algorithm was able to correctly identify which portions of the field of view were safe to land, and which were not. For cases where the stereo range map contains more noise than expected, the SLAD algorithm is more constrained by the additional surface roughness and

Figure 9. Landing site selection results from 24 m AGL over a gravel surface.

could potentially reject areas that are safe for landing. This results in a conservative system where safe landing areas can potentially be deemed unsafe because of the additional noise.

Figure 9 shows the SLAD results from 24 m AGL for one particular landing to a gravel surface. The landing zone contained a golf cart (1.8 m tall) and two boxes (1.6 m tall). For gravel, the stereo ranging performance is similar to grass, and the roughness constraint is set at 1.0 m from 24 m AGL. For this case, the box near the center of the image is recognized as an obstacle and rejected as a safe point to land. The chosen safe landing point (shown with the black circle) is within the safe region and maximizes the distance from the box and the edge of the window.

CONCLUSIONS

This paper provided an overview of the PALACE program and the methods of integrating the machine vision technologies with realistic vehicle dynamics and control laws for autonomous landings of RUAVs. Results from flight trials to evaluate and verify the performance of the machine-vision components were reported.

The results show that precise autonomous landings to unprepared sites are possible without ground-based instrumentation or markings, and without GPS. This has been demonstrated in-flight with upwards of 40 successful landings to date on various surfaces and obstacle fields.

A comparison between the quantitative objectives of the PALACE program (listed in Table 1) and the values measured in flight is shown in Table 3. The vision-based self-localization system is able to meet the requirements of drift (landing accuracy) and processing time with a performance that this robust for different surfaces, lighting conditions, and atmospheric conditions. The landing site selection algorithm was also able to meet the requirements by rejecting surfaces with obstacles greater than 10 cm at a success rate greater than 98% with a calculation time of less than 3 seconds.

Table 3. PALACE program quantitative metrics and flight measured values.

Quantitative Metric	Project Objective	Measured Values
Landing Site Size	< 7.0 m	< 7.0 m
Landing Surface Slope	< 15 deg	< 15 deg
Landing Surface Roughness	< 10 cm	< 10 cm
Landing Accuracy	< 1.25 m	< 1.00 m
Feature-Tracking Time	< 100 msec	< 60 msec
SLAD Calculation Time	< 5 sec	< 3 sec
SLAD Success Rate	> 98%	> 98%

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25th Army Science Conference
Nov 27-30 2006 -- Orlando, FL

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JPL

Presentation Outline

- PALACE program overview
- Machine vision technologies
- PALACE flight trials
- Conclusions / current status

PALACE

Precision Autonomous Landing Adaptive Control Experiment

- **Motivation:**
  - Requirement for precision autonomous UAV VTOL landing capability at unprepared sites (GPS occluded or denied) in variable winds
  - Enable perch and stare surveillance, precision UAV supply delivery and FARP operations, recovery, ground loiter and forced landing contingencies
  - Potential Applications:
    - Fire Scout, MAV (ducted fan), etc.
    - Manned platforms, brown-out, etc.
- **Key Challenges:**
  - Non-cooperative landing site
  - Obstacles in landing zone
  - GPS denied/occluded environment
  - On-board intelligent decision making

PALACE

Precision Autonomous Landing Adaptive Control Experiment

- **PALACE Approach:**
  - Machine vision algorithms for landing site selection and self-localization without GPS
  - Simulation environment to integrate and evaluate real-time vision routines, and vehicle dynamics and control
  - Advanced control modes for transitions between machine vision, GPS, Inertial Navigation, etc. on autonomous test-bed
  - Validation and flight trials of landing capabilities on Yamaha RMAX
  - PALACE work performed under a three-year Army ATO (IV.AV.2003.01)
    - Concluded end of FY05

Presentation Outline

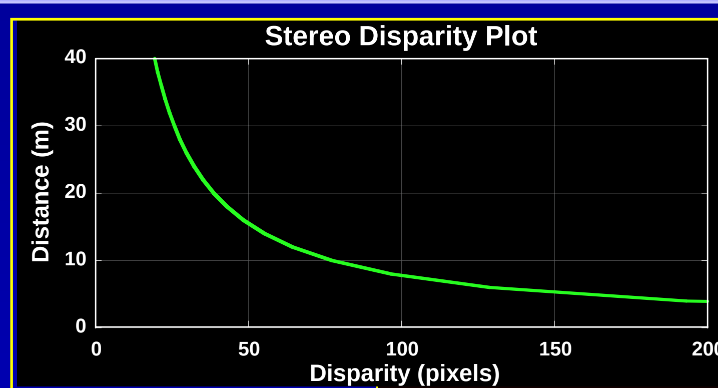
- PALACE program overview
- **Machine vision technologies**
- PALACE flight trials
- Conclusions / current activities

Stereo Range Mapping

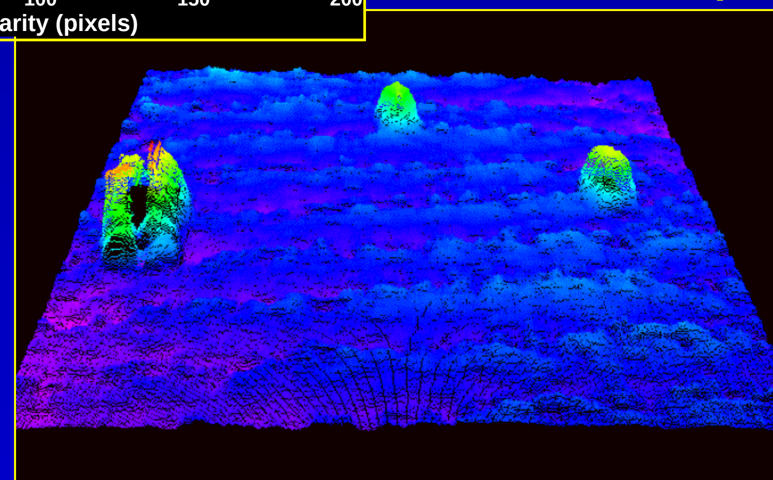
Right Camera Image

Left Camera Image

Pixel Disparity



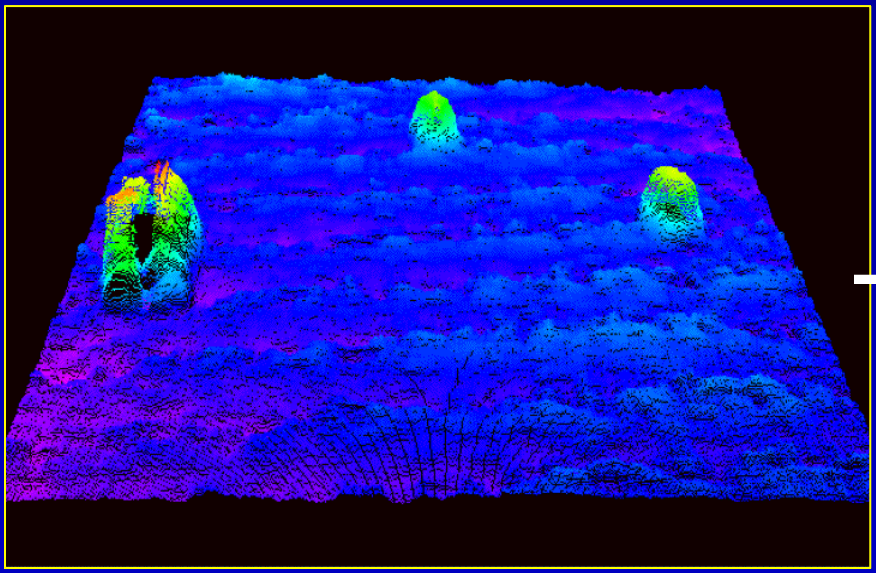
Elevation Map



- **Elevation map in inertial coordinates calculated using stereo images:**
  - Based on disparities between features in left and right images
  - Corrected for camera mounting angle and helicopter attitudes
- **Processing time varies with resolution (approx. 1-5 seconds)**

Safe Landing Area Determination (SLAD)

Elevation Map

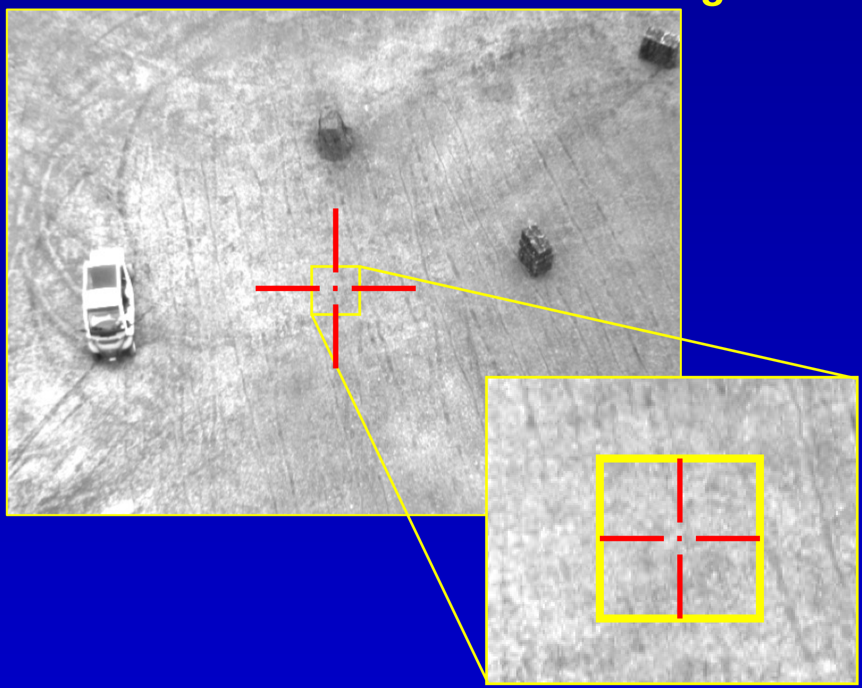


Landing Site Selection Results

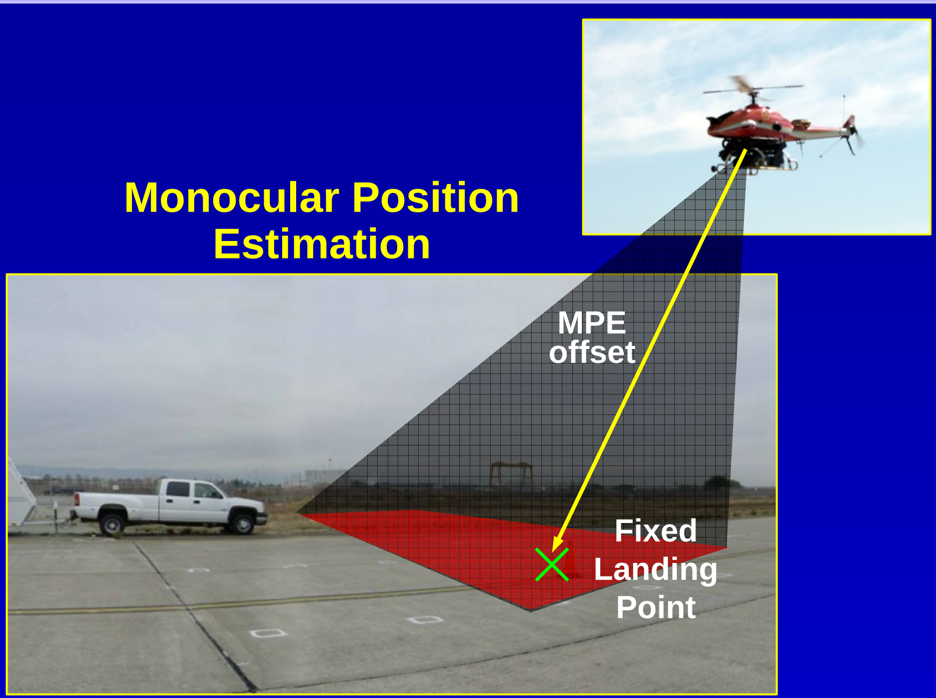
- **SLAD algorithm finds all valid landing sites by applying constraints:**
  - Landing point slope must be below a maximum (15 deg for this case)
  - Open area diameter must be above a minimum (7m diameter for RMAX)
  - Obstacle sizes (surface roughness) must be below a maximum (based on altitude)
- **Optimum landing point best meets constraints (1-2 sec. of processing time)**
- **SLAD algorithm works separately from the stereo ranging and can be used with range maps from any sensor (passive or active)**

Monocular Position Estimation (MPE)

Machine Vision Feature Tracking



Monocular Position Estimation



- **Feature tracking algorithm locks onto selected landing point**
- **Self-localization with respect to fixed landing point using:**
  - Pixel location within camera image
  - Laser slant range to center of camera image
  - Helicopter attitudes and heading
- **MPE system provides position estimates at 10Hz (same rate as GPS)**

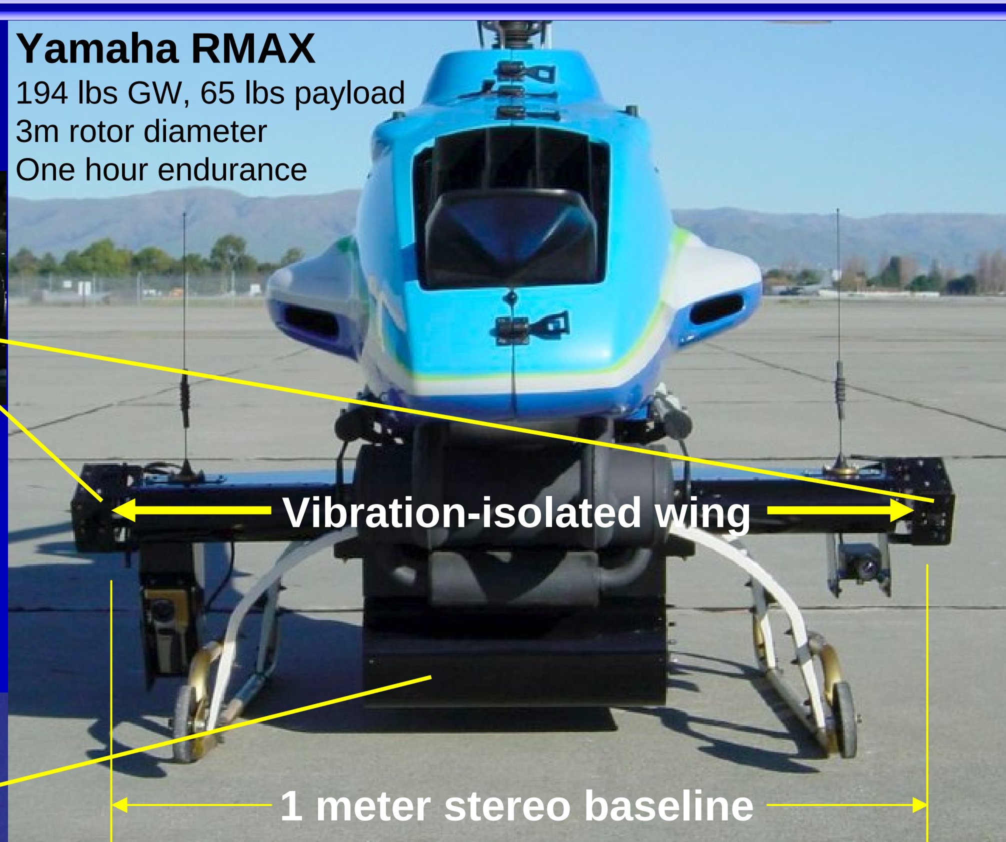
Presentation Outline

- PALACE program overview
- Machine vision technologies
- **PALACE flight trials**
- Conclusions / current activities

PALACE Flight Demonstration Vehicle

Autonomous Rotorcraft Project (ARP)

Monochrome digital cameras



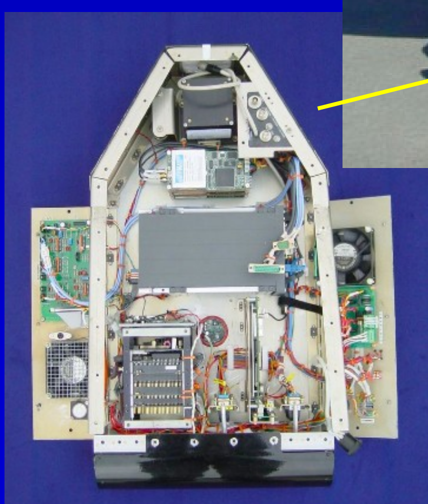
PALACE Components:

- IMU data (airframe)
- GPS data (airframe)

- Vision processing computer
- Two digital cameras (stereo)
- Laser range finder

Estimated system weight:

- 5 pounds



Avionics Payload

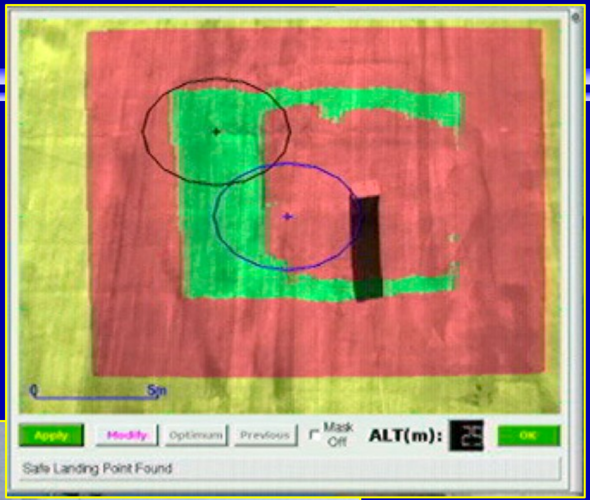
Crossbow AHRS IMU
Ashtech DGPS
PC104+ flight control computer
Compact PCI experimentation computer

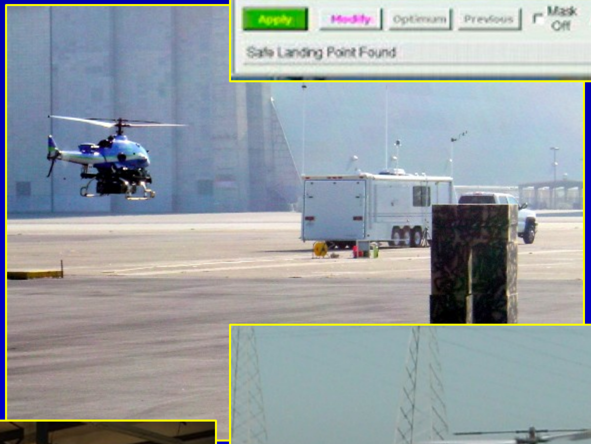
Laser range finder

Flight Performance Evaluation

PALACE Flight Testing and Demonstration:

- Component flight trials:
  - MPE performance for hover, descent and landing
  - Stereo ranging performance with different surfaces
  - SLAD performance with different obstacle fields
- Integrated landing system flight trials to verify PALACE system functionality, transitions and mode switching
- Approximately 30 flights for PALACE development, validation and evaluation testing
- Public flight demonstration:
  - January 31, 2006
  - ~ 40 attendees from industry, government and academia



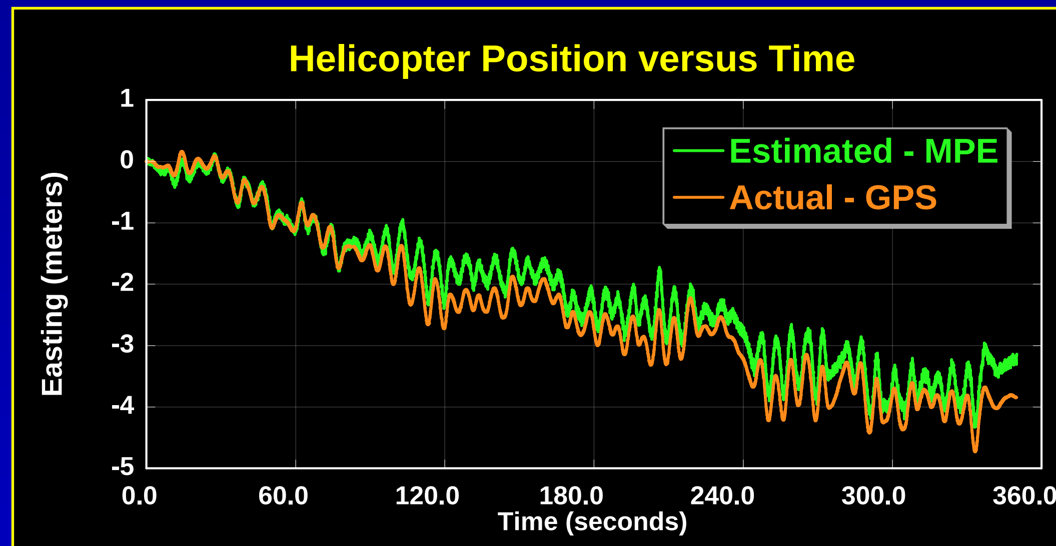


Autonomous Landing Video -- Flight

QuickTime™ and a
decompressor
are needed to see this picture.

Monocular Position Estimation Flight Evaluation

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



Vision-Based Localization -- Key Results:

- Tracking drift of < 1m in 6 minutes of maneuvering without GPS -- Typical result
- System performance is robust to various:
  - Surfaces (grass, concrete, asphalt, gravel)
  - Lighting conditions (overcast, sun)
  - Atmospheric conditions (wind speed, direction, turbulence)
- System runs at 10Hz -- MPE processing time is 45 msec

Stereo Ranging Flight Evaluation

Obstacle Height Resolution

Altitude AGL (m) / Obstacle Height (m)	6 m	12 m	18 m	24 m	30 m
0.2m	0.22 (10%)	0.20 (0%)			
0.6m		0.63 (5%)	0.62 (3%)		
0.9m			0.97 (7%)	0.80 (11%)	1.10 (22%)
1.5m				1.45 (3%)	1.70 (13%)

Obstacle Size Constraint Values

Height AGL (m)	Allowable Obstacle Size (m)
	Measured for asphalt
30	1.2
24	0.8
18	0.4
12	0.25
6	0.10

Stereo Ranging -- Key Results:

- Stereo performance fairly independent of surface texture (grass, concrete, asphalt, gravel)
  - Some dependence on surface directionality and lines
- Measured obstacle heights were within about 20% of actual height for all cases:
  - Results improve to within 10% below 20m AGL
- Stereo ranging accuracy/resolution improves as the altitude decreases during descent:
  - Reject obstacles >10cm from 6m AGL

Landing Site Selection Flight Evaluation

SLAD from 30m AGL

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

SLAD from 24m AGL

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

SLAD from 18m AGL

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Autonomous Landing Site Selection -- Key Results:

- Landing site selection algorithm effectively refines the location of the landing point and the helicopter descends and terrain sensing becomes more accurate:
  - Reliably rejects sites with obstacles > 10cm in height
- Obstacle size constraint values must be tuned to produce good SLAD results:
  - Key is accurate stereo range data (real-time sensing)

Quantitative Metrics

- Measured performance metrics in flight were evaluated against the objectives of the PALACE program

Quantitative Metric	Project Objective	Measured Values
Landing Accuracy Position Estimation Time	< 1.25 m < 100 msec	< 1.00 m < 50 msec
Landing Surface Slope Landing Site Size Allowable Obstacle Size SLAD Calculation Time SLAD Success Rate	< 15 deg < 6.25 m < 10 cm < 5 sec > 98%	< 15 deg < 6.25 m < 10 cm < 3 sec > 98%

Conclusions

- Precise autonomous landings to unprepared sites are possible without ground based instrumentation and without GPS
  - Fully autonomous with all decision making and processing on-board
  - No operator interaction required
- All objective performance metrics were met
  - Repeatable and robust with > 40 successful landings to various surfaces and obstacle fields
- Concludes 3-year successful S&T program to demonstrate autonomous landing system feasibility --> Good basis to move forward with a more directed application

Current Status and Potential Applications

Current Status:

- TRL 6 -- Prototype system demonstration in a relevant environment
- Higher TRL requires:
  - Prototype hardware needs hardening and qualification
  - Additional flying is required in less than ideal conditions -- Fog/smoke, rain, etc.
- Investigating passive (EO cameras) versus active (scanning laser) terrain sensing for autonomous landing
  - American Helicopter Society UAV Specialists Meeting paper (Phoenix, AZ, January 2007)
- PALACE work is part of a larger program at the AFDD investigating obstacle field navigation and UAV control and flying qualities

Potential Future Applications:

- VTOL UAV autonomous landing, including Firescout, MAV (ducted fan), etc.
- Possible application to manned aircraft for: emergency landing, precision landing, situational awareness and landing in degraded visual environments (ie. brown-out)

PALACE

Precision Autonomous Landing Adaptive Control Experiment

Questions ?

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